CAAP Quarterly Report

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Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Contract Number: 693JK320NF0001

Project Title: *Holistic Electromagnetic and Ultrasonic NDE Techniques for Plastic Pipeline Aging and Degradation Characterization*

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For quarterly period ending *Feb 28, 2021*

Business and Activity Section

(a) Contract Activity

The project is on schedule for spending and meeting deliverables.

(b) Status Update of Past Quarter Activities

In the past quarter, at MSU, literature review on the types and potential cause of the pipe degradation were performed. The electromagnetic properties change due to the degradation were studied. A set of pipe samples with different fabrication date and store conditions from GTI has been received. Preliminary experiments were conducted to study the properties change of the pipes. Simulation studies were performed to providing a better under understanding of the sensor design with different sizes and optimize the parameter of the multi-channel FSRR.

ASU starts to investigate the uncertainty quantification and maintenance optimization under uncertainties detailed in the Task 3 in the proposal during the past quarter. Specifically,

1. ASU starts to investigate the constrained Gaussian Process model and Neural Network model for classification and regression problems with measurements noise.
2. ASU starts to review literature articles on the stochastic maintenance optimization problems in infrastructure management.

As the research just started following the original proposal schedule, no detailed progress report from ASU is included in this quarter report and will be reported in the next quarter report.

(c) Cost share activity

The project's financial activities is managed by MSU OSP/CGA.

(d) Task 1: Near field microwave based flexible electromagnetic transducer

Introduction

Pipelines are used to transport large quantities of oil and gas products over long distances because of their safety, efficiency, and low cost. However, it is extremely important for safe operations to monitor these gigantic pipelines and accurately detect defects and aberrations. Leaks and breakages, if unnoticed, can cause significant loss to lives and properties. Different kinds of threats can occur in pipeline integrity, such as cracking, dents, third-party damage, weld, etc. Structural integrity assessment of plastic pipes by NDE methods is necessary.

Several ILI technologies that are in common for pipeline detection in the NDE domain are Magnetic flux leakages (MFL), Ultrasonic (UT) tools, Electromagnetic acoustic transducers (EMAT), Eddy currents testing (ET), etc. The aim is to detect various cracks and losses in Polyethylene and (PE) and PVC pipelines. The difference in pipelines' material properties stored in different environments (inside and outside) is subjected to a different temperature.
Thus, in this quarter, various electromagnetic-based NDE techniques have been reviewed for assessing the extent of degradation. Also, serval simulation-based studies have been performed to optimize the design of the sensor. In experiments, open-ended coaxial and resonant cavity-based waveguide have been employed to study the the change in dielectric properties in various pipes subjected to different conditions.

Literature study of the pipe degradation

There are 22 "root causes" of pipeline accidents as reported by Pipeline Research Council International (PRCI).

Table 1: Different Defect Types occurring in PE pipes

	Different Defect Types
1	Corrosion (Internal & External)
2	Stress Corrosion Cracking (SCC)
3	Defective Pipe (DP)
4	Defective Pipe Seam (DPS)
5	Defective Fabrication Weld (DFW)
6	Defective Girth Weld (DGW)
7	Construction Damage (CD)
8	Malfunction of Control or Relief Equipment (MCRE)
9	Stripped Threads, Broken Pipe, or Coupling Failure (TSBPC)
10	Gasket Failure (GF)
11	Seal or Pump Packing Failure (SPPF)
12	Incorrect Operations (IO)
13	Third Party Damage (TP)
14	Previously Damaged Pipe (PDP)
15	Vandalism (V)
16	Earth Movement (EM)
17	Heavy Rains and Floods (HRF)
18	Lightning (LIGHT)
19	Cold Weather (CW)

As per ASME B31.8S standard nine primary threat conditions are identified which follows three broad categories.

- Time-Dependent Threats (threats growing with time): These threats increase with passage of time. These threats are partially prevented by addition of protective measures such as coating However they are regularly monitored by several in-line inspection methodologies. Different time dependent threats are as follows and they form an essential integrity analysis for Structural integrity program.
    - Internal Corrosion
    - External Corrosion
    - Stress Corrosion Cracking

- Resident threats: These threats do not grow with passage of time; however, they tend to act when influenced by other failure mechanisms. These threats are monitored by close inspection such as pressure test after installation and are mostly stable threats.
    - Manufacturing
    - Fabrication
    - Construction
- Time independent threats: These threats occur under the influence of an external force. Most common of these threats occur in pipeline due to erosion, operator error during excavation and/or operations. Though these threats are not so dangerous like the time dependent threats but proactive monitoring such as maintaining proper operating guidelines, proper training for onsite personnel is essential to mitigate them.
    - Human error
    - Excavation Damage
    - Earth movement, outside force or weather.

Among all these threats the most predominant are the Internal Corrosion and External Corrosion. Internal corrosion is caused by the materials that are being transported by the pipeline. Plastic Pipeline are degraded by the liquids and gases that they carry as these gases and liquids are corrosive whereas external corrosion of pipeline is caused by the external environment. The acidity and the moisture content of the soil, exposure to temperature are the most common factors for external degradation. Fatigue has significant contribution in causing the threats. Pipeline integrity management is essential as these threats have a high probability to cause failure. Moreover, threats can interact among themselves thereby increasing the probability of failure.

High-density polyethylene (HDPE) and polyvinyl chloride (PVC) are most commonly for plastic pipes. Advantages of using plastic pipe are as follows:

- Abrasion resistance
- Chemical corrosion resistance
- Low maintenance
- Long life expectancy

The most common types of degradation in plastic pipes are Environmental Stress Cracking (ESC) and ultraviolet light degradation. Pipelines subject to external environment and temperature for a long time are more prone to degrade with time. The properties of the plastic pipes can be affected by Liquid hydrocarbons such as gasoline and oil. Hydrocarbons permeate the pipe wall leading to swelling and strength loss. Hence timely detection is required. Plastic may become brittle due to Photo-degradation and thereby resulting in crack formation.

Failure Mechanisms

Two general crack propagation mechanisms occur in polyethylene pipes under constant loading:

- Ductile failure: Dominated by large scale deformations.
- Brittle failure: Starts at stress concentration points and propagates slowly preceded by a craze zone.

Slow Crack growths (SCG) follow both the above-stated mechanisms. Here we are assessing the failure mechanism in PE pipes. The aberrations in the plastic pipes will be detected by different EM methods due to change in dielectric properties. The basic principle of material testing that will be used in this quarter and the next quarter is shown in the below schematic. The polyethylene samples will be subjected to heat treatment, and thus there will be morphological changes, mostly change in thickness due to the effect of temperature. Various electromagnetic NDE methods will then detect these dielectric changes like change in permittivity, dielectric strength, resistivity.

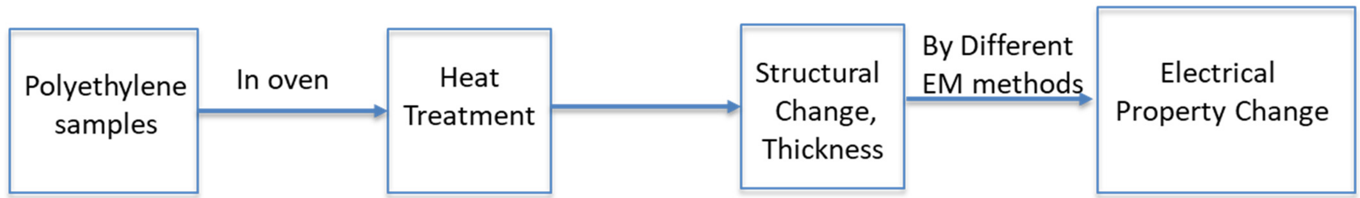

Figure 1: Steps for thermal degradation of PE samples in lab

PE samples will be heated, which will affect the morphology of the samples. These morphological changes will result in changes in electrical properties. If a specific sample is heat-treated and later tested for morphological and dielectric property changes due to heat treatment, one can determine their relationships. The goal is to conduct a series of experiments from which it would be possible to see the correlations between these factors' direction and interdependency. Thermal exposure will affect both the morphology and physical dimensions of the sample as there will be a change in the thickness of the sample. HDPE is mostly used to manufacture pipes as they have a high melting point and high crystallinity, and thus, the material becomes stiffer.

Different Stresses on Pipeline:

PE pipelines are subjected to undergo brittle like fracture under service conditions when subjected to low stresses or temperature for a long period of time. This leads to Slow Crack Growth (SCG). Figure 4 shows the failure modes occurring due to loading and other environmental conditions. Stress cracking (SC) is critical as it leads to creep or fatigue related failures. Ductile failures are generally characterized by large-scale material yielding adjacent to failure location. It is more expressed as applied stress gets higher. On the other hand, brittle failure in pipes is characterized by lase deformation and is generally a long term mechanism. Temperature accelerates brittleness from sustained pressure tests. Ductile failure is associated with macroscopic yielding and the time of failure is determined by the creep rate whereas brittle failure is associated with crack growth. Figure 4 shows various failure mechanisms in PE pipes.

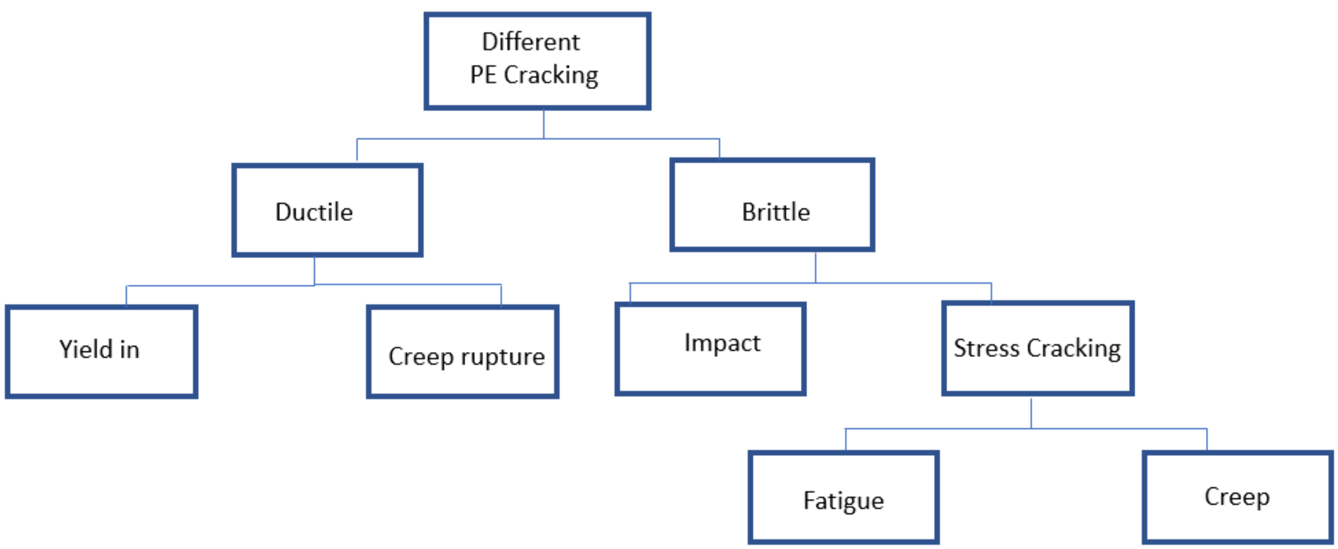

Figure 2: Different failure mechanisms due to loading

Pressurized pipes are subjected to various stresses, the most common of these is the hoop stress σ_H. Figure 5(a) shows the hoop stress acting on a pipe wall. The hoop stress is given by:

$$\sigma_H = \frac{P_{inner} D}{2t}$$

Where σ_H is the hoop stress in MPa, P_{inner} the internal pressure in MPa, t the pipe wall thickness in mm and D the outside diameter measured in mm.

On ignoring tangential shear stress, the Von Mises longitudinal stress is expressed as shown in Figure 5 (b)

$$\sigma_E = (\sigma_H^2 + \sigma_L^2 + \sigma_H \sigma_L)^{1/2}$$

Where σ_L the longitudinal stress is given by: $\sigma_L = thermal\ stress + Bend\ stress + 0.3 * hoop\ stress + End\ cap\ stress$

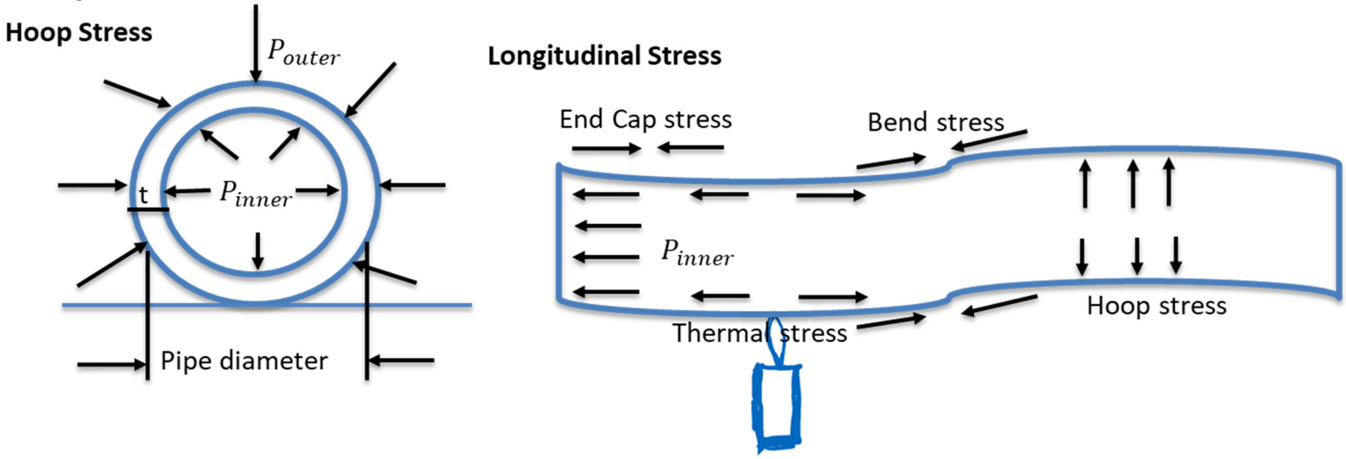

Figure 3: Different stresses acting on PE pipes.

Now if the hoop stress is known then for a given temperature the time to failure is given as:

$$Logt = A + \frac{B}{T} + \frac{BLog\sigma_H}{T}$$

Where t is the time to failure, A, B are constants acting on system, T temperature in Kelvin.

Environmental Stress Cracking (ESC) mechanism:

Environmental stress cracking (ESC) in plastics occurs due to pressure (internal and/or external) acting in the presence of surface-active substances such as soaps, dyes, agents containing moisture [7]. These stress cracking agents accelerate the brittle formation within the pipe segment; however, it is not a chemical reaction. ESC of polymers is similar to that of stress corrosion in metallic pipes. Plastic deformation takes place over a period of time as it takes some time for the stress cracking agent to penetrate the micro-cracks from which failure is initiated. ESC increases with an increase in temperature. PVC, PE being semi-crystalline, amorphous structures facilitate fluid permeation into its loose structures, promoting crazing, cracking, or plasticization. Crazes are expanded regions held together by fibrils bridging the micro-cracks and thus preventing their propagation and coalescence. As the cohesive force gets lowered, this facilitates cracking. The first step of the failure process is the embrittlement of the polymer. Then the crack initiation takes place, which is favored by the acting load [9,10]. The presence of macroscopic cracks marks the characteristics of ESC type of failure, and a fibrillar structure of the craze formed ahead of the damage. However, external stress should act for crack initiation. The liquids that are being transported by the pipelines get absorbed and thus act as catalysts for creating the ESC failure. These stress cracking agents reduce the yield strength of the polymer and lead to fracture. The fracture may be either ductile or brittle, depending on stress and time considerations. Diffusion of these surface molecules into the polymer due to stress results in increased chain mobility, which reduces the activation energy, thereby lowering the cohesive force among the molecules.
Hence, ESC depends on the concentration of stress cracking agent, exposure temperature, exposure time, and the strain level of the polymer used in the pipe. Thus, interaction among material integrity, environmental parameters, and stress-strain relationship all play a role in ESC of plastic pipes, as shown in figure 6 (a).

Figure 6 (b) shows the change in mechanical properties (young's modulus) when PE sample is in air and is subjected to other aggressive chemicals [8].

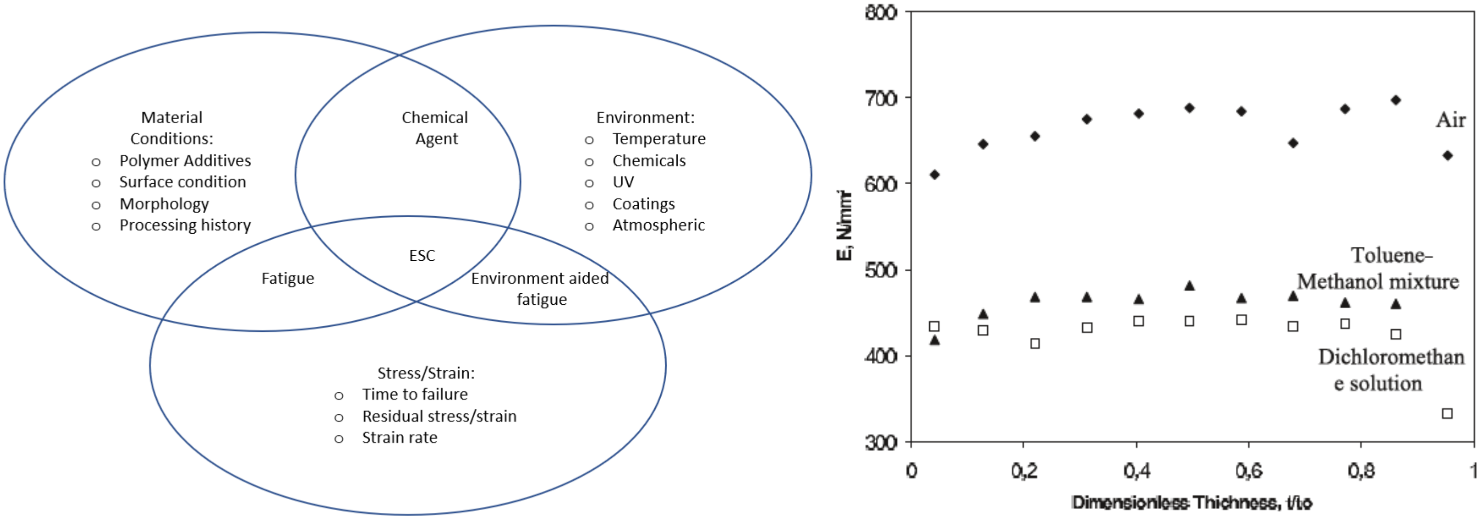

Figure 4 (a): Different factors leading to ESC, (b): Youngs modulus comparison in air and in other aggressive environments [8]

Previous literatures are there which study the detection of ruptures in pipeline coatings and surface faults using split ring resonators-based sensor [11,12]. But there is no study assessing the material degradation in PE and PVC pipes due to exposure to different environments, different times, degradation due to ESC and Plasticizer losses.

Simulation

In this quarter, more simulations have been performed to understand the FSRR sensor design better.
One of the simulation studies focuses on the multi-channel design. Multiple channels with multiple ring-sensors will cover a larger area that improves the scanning speed and allows the system to monitor various points simultaneously. However, the sensors assigned to different microstrip lines may have interference with each other. Therefore, FSRRs with two microstrip lines at different locations have been simulated.

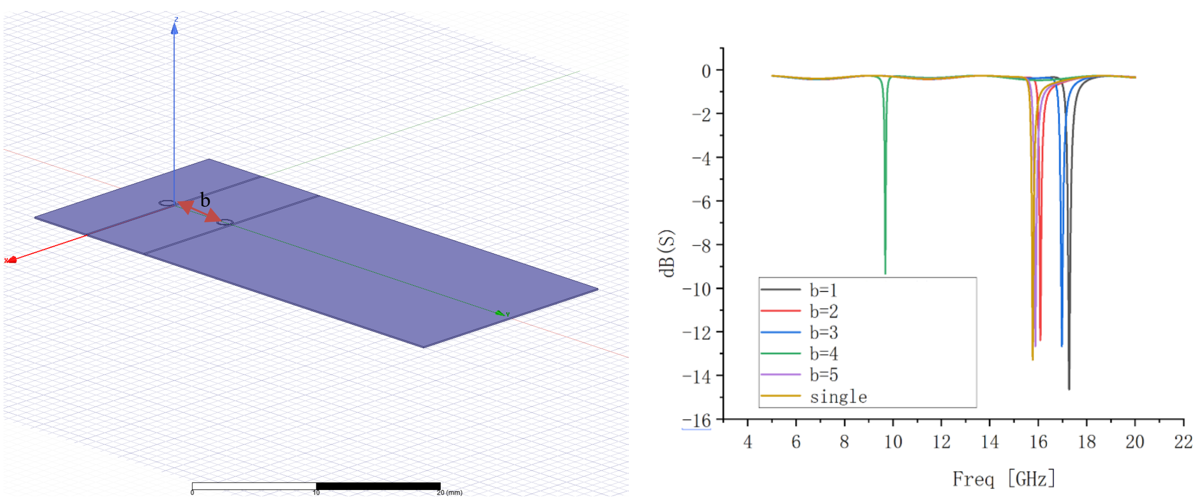

Figure 5 Multi-channel FSRR simulation with different distance between the microstrip line

As shown in Figure 5, b is the distance between the second channel’s copper ring to the first channel’s microstrip line(unit: mm). The simulation results show that the interference decrease as the distance increase. When b is 5 mm, the signal response of S12 is very close to the single channel's signal, which means the interference is almost neglectable.

Another set of simulations focus on the size of the sensor. The small size of the FSRR provides advantages such as better resolution and results in the many difficulties of the fabrication. Therefore, the simulations that study the performance of the sensor with a larger size have been performed.

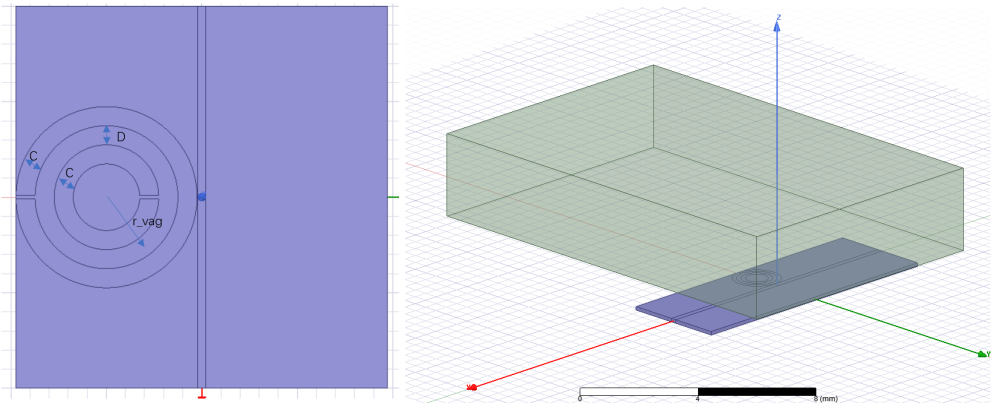

Figure 6 Simulations for the larger size sensors.

C is the width of each copper ring, and the r_avg is the average radius of the two circles. A large PVC sample (DC = 4) has been placed on the top of the sensor with a 1mm lift-=off distance. A parametric study that simulates the sensor responses at different sizes has been performed, and the results are shown in Figure 7.

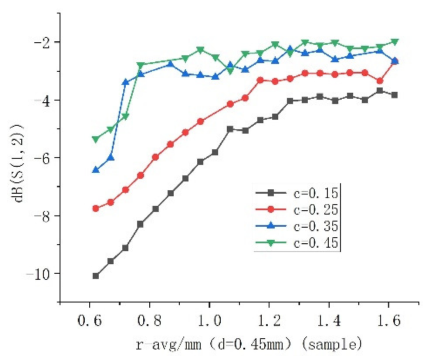

Figure 7 Simulation results for the sensor with different line width and radius.

As the ring's size increases, the magnitude of S_{12} increases, which indicates the Q factor of the sensor becomes worse. A larger sensor size means a larger scanning area and more straightforward fabrication process and worsens resolution and compromised sensitivity.

Experiments

In this quarter, serval preliminary experiments have been performed to study the properties of the pipes with different storage conditions. There are serval methods that can be used to get a estimation of the pipeline material's electromagnetic properties:

- Transmission line/ Reflection Line methods
- Open ended coaxial cable
- Resonant cavity method (using waveguide and split ring)
- Free space method

In Transmission/Reflection Line, only the fundamental waveguide mode is propagated. In an open-ended coaxial cable, only the TEM or TE mode is propagating. In resonant mode, TE or TM propagates, and it provides high accuracies.

In the Transmission line method, the Material under test (here the pipe samples) is placed in a coaxial line section, and the two ports' complex parameters are measured with a VNA. After calibrations, measurements are conducted, and the measured scattering parameters relate to the complex permittivity and permeability of the sample under test from which material degradation is evaluated. Figure 8 (a) shows this method's setup; however, the measurement accuracy is limited by airgap effects and lift-offs. The free space method allows measurements on MUT under diverse environments and a wide range of frequencies. Here the MUT can be large and flat and is thus an efficient method for pipe monitoring. Figure 8 (b) shows the working principle where two antennas are placed facing each other connected by a network analyzer. After calibration, the s-parameters are evaluated by placing the pipe in between the antennas. However, there will be multiple reflections between the antennas and the MUT, and the diffraction effects at the sample edge are to be nullified. The resonant method is the most accurate method to obtain the dielectric measurements. Here we will use resonant methods such as waveguides and split-ring resonators. As the resonance characteristics depend on the MUT in a cavity, the quality and resonant frequency are monitored to determine the dielectric parameters. At first, the dielectric properties of the empty cavity are measured, and then the dielectric properties are measured along with the MUT. Figure 8 (c) shows such arrangement, and the preliminary scanning results are shown in Figure 9.

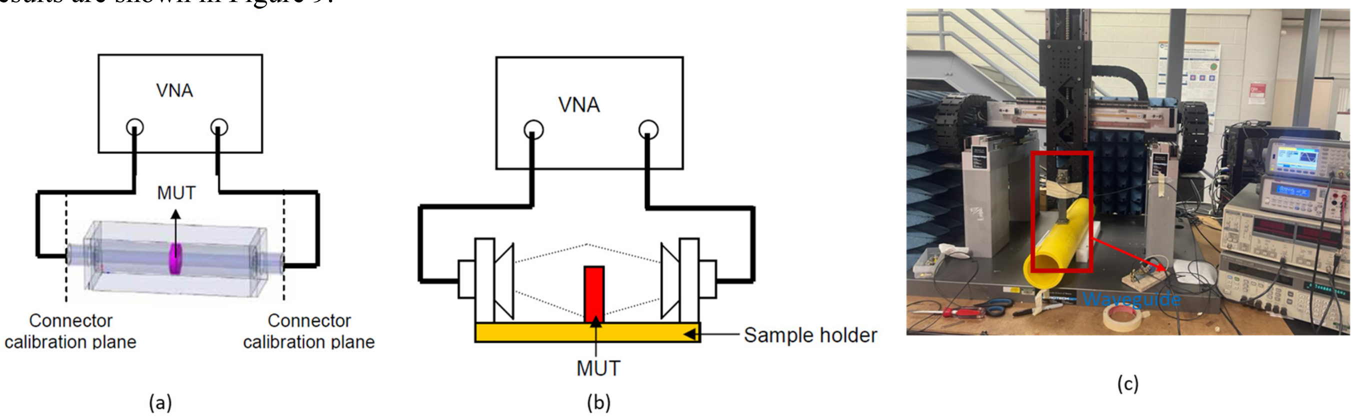

Figure 8: Different experimental setups to measure the dielectric properties of MUT

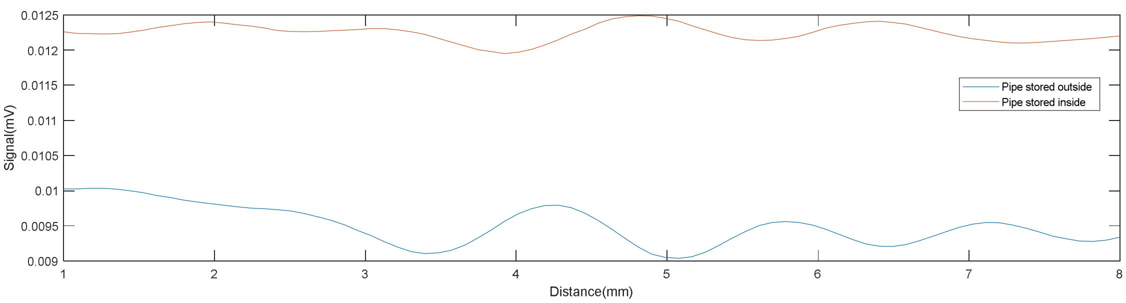

Figure 9 Preliminary scanning results of the pipes with different stored conditions

In order to have a better and more accurate estimation of the material's properties, more studies and experiments are planned for the next quarter.

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